

FLAME BASE STRUCTURE OF SMALL-SCALE POOL FIRES

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TEMPERATURE MEASUREMENT BY HOLOGRAPHIC INTERFEROMETRY IN LIQUIDS

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ABSTRACT

Detailed temperature measurements of the condensed phase are important for the study of flame spread over liquids and liquid-pool fires leading to boilover. The measurement requires high spatial resolution near the interface between liquid and gas, where a steep temperature gradient is formed and that controls heat-transfer process between the two phases. Conventional thermocouple techniques have limitations on accurate measurements in this type of sensitive location because the thermocapillary effect of the thermocouple bead significantly distorts the original temperature structure near the interface. To avoid such interference, we developed a holographic interferometry (HI) technique that is non-intrusive and is capable of detecting nearly simultaneously a sudden and minute temperature change occurring in a distributed area. The thermo-optical coefficients of liquids are two orders of magnitude higher than that of gases. Therefore, if an interferogram was obtained simultaneously for the interface region between a gas and a liquid, the gas phase hologram is two orders of magnitude less sensitive than the liquid phase hologram. To enhance the sensitivity in the gas phase, a dual wave-length holography was applied. In this study, we show that HI is a very useful temperature measurement technique, and the estimated errors are so small that they cause no significant errors when the HI data are used for quantitative analysis. This paper summarizes recent progress made on the application of HI to highly transient phenomena, such as the studies of flame spread and liquid-pool fires.

INTRODUCTION

As demonstrated in our previous studies on flame spread over liquids [1] and pool fires on liquids [2], an accurate knowledge of the transient temperature profiles in the condensed phase is necessary for the understanding of the control mechanisms of such transient phenomena. This paper summarizes recent results of applying the HI technique to flame spread over liquids and pool fires leading

to boilover [3,4]. An accurate measurement of temperature profiles in the condensed phase requires an instantaneous temperature mapping capability that includes high resolution in space and time and simultaneous collection of spatially distributed signals. A conventional point-by-point measurement technique using a thermocouple, however, is incapable of satisfying these requirements because of the disturbing effects of the wire on the condensed phase, the limited spatial resolution of the thermocouple bead, and the limited response time of the thermocouple [3,4].

A holographic interferometer connected to a photographic recording system can instantaneously detect a sudden and small temperature change occurring over a distributed area. Previously [1] detailed temperature profiles in the subsurface-liquid-convection current were investigated using this technique. Basic principles of this method were given by Ito and Kashiwagi [5], and their applicability was successfully demonstrated for 1-decene by Kashiwagi and Kashiwagi [6] and for polymethylmethacrylate by Ito and Kashiwagi [4]. Previously, detailed temperature profiles in three different alcohols (methanol, ethanol and n-propanol) were measured under a spreading flame condition. The HI study revealed a detailed temperature structure consisting of two counter-rotating circulation zones in the liquid phase under the flame front.

Pool fires leading to boilover were also studied using the HI technique. Boilover, the phenomenon where the water sublayer begins to boil, penetrates the fuel layer, and ejects fuel and water drops into the surroundings, is a complex phenomenon and its mechanism has not yet been fully understood [7,8]. Using the HI technique, we studied the effect of the boiling water sublayer that always occurred prior to the boilover. This study provided detailed temperature distributions in the fuel that overlaid the water and of the fuel-water interface [9], detailed and instantaneous temperature mapping not possible with conventional thermocouple measurement. Based on the HI data, we developed a model to predict the onset time of boilover, which is characterized by the onset of an intense spattering of water and fuel droplets [9].

SINGLE WAVE-LENGTH HI

Flame Spread Experiment

A schematic of the experimental apparatus including fuel trays of 40 cm length, 1 cm height and five different widths (0.5, 1.0, 2.0, 4.0 and 5.0 cm) with a temperature controlled rectangular cooling unit, and a video camera is shown in [1]. The x-coordinate is fixed along the fuel surface (+ downstream of flame front and - upstream of flame front). The y-coordinate is along the vertical direction (+ to air; - to fuel). The z-coordinate is normal to the x-y plane and the origin is fixed to the leading-edge of the moving flame on the fuel surface along the center line of tray. A schematic diagram of the optical system used for holographic interferometry is shown in Fig. 1. Lenses and mirrors are arranged on an optical bench and a 5-mW He-Ne laser was used as the light source. A

refractive index of Pyrex). L_s is the thickness of Pyrex wall, λ is the wavelength of the laser beam, and T_∞ is the initial liquid temperature. The thermo-optic coefficient of Pyrex is one order of magnitude smaller than that of the liquid. The thickness of the Pyrex wall is 0.1 cm, which is small compared to the width of the tray. An error estimate was made for the case of Pyrex with 0.1-cm-wall thickness and 0.5 cm width; it was found that the error is not more than 1% of the temperature of the liquid. Therefore, the second term on the left-hand side in Eq. (1) can be neglected.

The reference temperature for the interferogram was obtained with a copper-constantan thermocouple made from 50 μm wire. The spatial resolution for the fringes in interferograms is 30 μm . The accuracy of controlling the liquid temperature is $\pm 0.5^\circ\text{C}$. It should be noted that along with the accuracy of our interferogram, the following three effects are important and should be estimated accurately.

(1) The accuracy of the temperature dependence of the estimated thermo-optic coefficient must be obtained. Thermo-optic coefficients for alcohols and hydrocarbon liquids below 25°C were investigated experimentally by Hauf and Grigull [10] and theoretically by Murphy and Alpert [11]. However, their temperature dependencies are unknown. Therefore, we measured the thermo-optic coefficients of four different alcohols (methanol, ethanol, n-propanol and n-butanol) as functions of temperature between 2°C and 80°C using an Abbe refractometer. The measured values were correlated by a quadratic equation. The thermo-optical coefficients were then obtained by taking derivatives and they compared favorably with those at 25°C by Hauf and Grigull [10]. The observed difference is less than 1%.

(2) The error due to refraction of light was estimated from the equation described by Ito et al. [12]. The maximum error is estimated to be 0.8°C (0.64%) assuming $(dT/dy) = 250^\circ\text{C}/\text{cm}$ and tray width is 0.5 cm.

(3) The error due to temperature variation in the liquid along the light beam, which is caused by heat loss to the wall, must be measured. The fringe number is determined by integrating the temperature distribution along the path length and dividing it by the path length. The difference between the temperature at the center of the liquid along the path length and the average temperature is less than 1% of the temperature at the center of liquid.

As a result, the estimated total maximum error from steps (1)-(3) above does not exceed 3% of the temperature at the center of liquid; thus, holographic interferometry is accurate enough for us to pursue our objective.

A series of six interferograms for propanol (flash point = 25°C) can be seen in [13]. These interferograms can be used to qualitatively study the flow structure in the liquid phase and temperature structure in the gas phase. However, quantitative information may not be easily deduced from these interferograms due to the three dimensional structure of the subsurface-liquid flow. To demonstrate the HI technique for the use of quantitative analysis, a representative interferogram and an illustration of the corresponding isothermal lines are shown in Fig. 2. The interferogram was taken for flame spread over propanol whose initial temperature was 21°C and the flame spreads with a

constant velocity without pulsation. The HI technique revealed a detailed temperature structure in the liquid phase. It is also sensitive enough to detect the subsurface-liquid convection-current. Therefore, quantitative information is available from the interferogram. Based on the interferogram results in Fig. 2 and gas-phase velocity-measurement results by Hirano et al. [14], it was found that gas-phase and liquid-phase-convection currents are important for preheating the liquid ahead of the flame [1]. Our HI found a double circulation structure, a thin layer of subsurface flow and a cold circular convective flow. Both are located underneath the flame leading edge (Fig. 2).

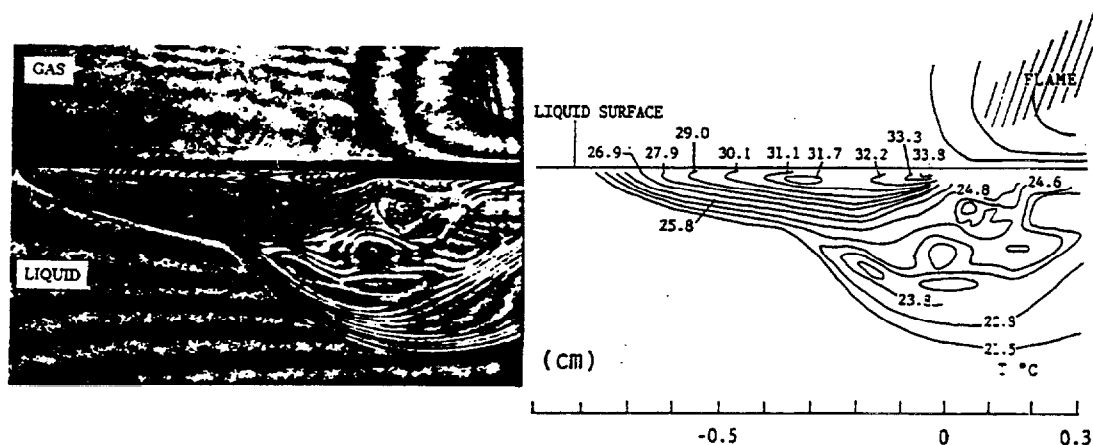


Figure 2 Liquid temperature-structure obtained by HI and its isothermal lines (1-propanol with initial liquid temperature, 21°C).

Boilover Experiment

Rectangular Pyrex containers were used [2] and a 35 mm motor driven camera with a telephoto lens was used to record the hologram with a shutter speed of 1/500, which was fast enough to "freeze" the diffraction image. Interferograms were taken at 1 to 0.1-s intervals depending on the phenomenon of interest. The optical system is the same as the one used for the flame-spread experiment (Fig. 1). The diffraction image was enhanced by increasing the intensity of the light so that a real time method could apply as demonstrated previously in the flame-spread experiments.

At the early stages of combustion, the liquid loses heat to the Pyrex free board. With continued combustion, the increased free board area is heated by the flame, and hence the heat is transferred back to the liquid. These effects can create a temperature gradient along the laser beam, causing errors when temperatures are determined from the interferograms. To estimate this effect, copper-constantan thermocouples made of 50- μ m-diameter wire were placed in the liquid and the Pyrex wall. The thermocouple wires were horizontal to the

fuel surface to minimize conduction loss. It was found that the temperature distribution in the Pyrex walls does not affect the results. The other errors involved in our HI system are estimated to be at most 3 % as shown in the section on the flame-spread experiment.

An interferogram is shown in Fig. 3. which is related to the onset of boilover, at 197 s after the ignition. Two dark lines can be identified; one is between the fuel and the water, and the other is between the gas phase and fuel surface. These dark lines are the result of steep temperature gradients which are beyond the capability of our HI temperature resolution. For $t < 40$ s, the interferograms revealed that a very steep temperature gradient existed only in the vicinity of the fuel surface, which was approximately 2 mm thick, and that a very gradual temperature change occurred in the water layer. At $t = 136$ s, the fuel layer shows dynamic motion consisting of small and large eddies. At the onset of boilover, $t = 197$ s, the entire fuel surface and the fuel-water interface are physically distorted. The distortion may be attributed to a dynamic effect of the superheated water sublayer due to sudden vapor expansion. The temperature at the fuel-water interface was determined from the interferogram to be 376 K. The actual temperature may be slightly higher than this because of the effect of deflection of light along the y-direction and the edge effect. The interferograms at $t = 197$ s and 202 s show that the strong convective motion generated in the water layer causes uniform temperature profiles in the fuel and water layers near the fuel-water interface.

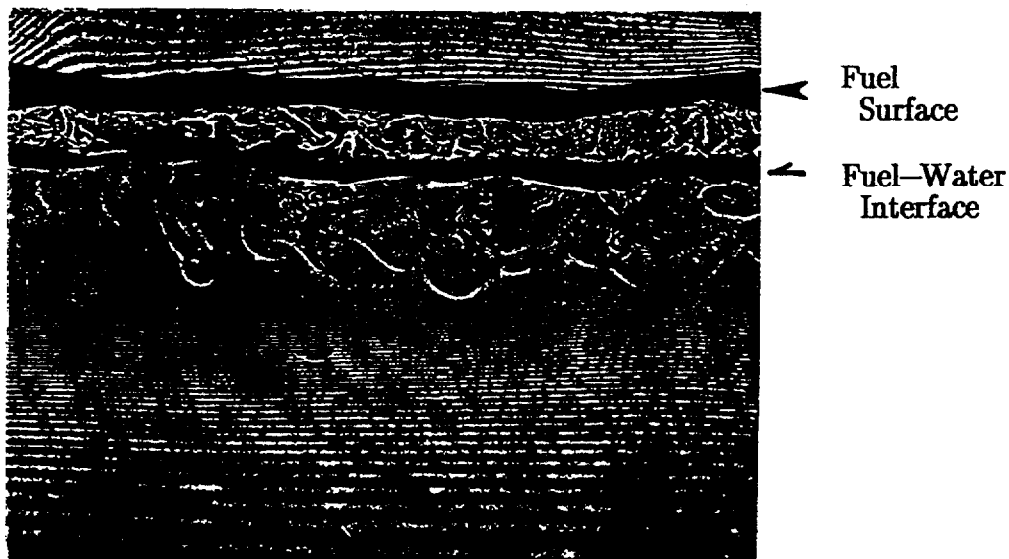


Figure 3 An interferogram obtained at time, $t = 197$ sec. after ignition (n-decane with liquid temperature, 21°C).

Dual Wave-Length HI

In the past, flame spread over liquids was studied as a function of initial liquid temperature [15-17]. When it is below the flash point, three different spread regimes are observed: those are in the order of decreasing the liquid temperature: (1) uniform spread regime, (2) pulsating spread regime, and (3) quasi-uniform spread regime. According to the definition of flash point, when the liquid temperature is below the flash point, flame spread is not possible; but it can be achieved by preheating the liquid by an ignition source. Once a flame is initiated on the liquid surface, heat will be transferred from the flame to the liquid, raising the local liquid temperature above the flash point. There are two different types of flash point that can be experimentally determined: open-cup flash-point and closed-cup flash-point. If the flame spread is tested under open-cup conditions, the liquid temperature should be below the open-cup flash-point. However, a problem arises when the open-cup flash-point is experimentally determined, because it easily fluctuates several degrees around the average value; likely due to the fluctuation of gas-phase fuel-concentration.

This may cause confusion when experimental results are interpreted by blindly accepting the ill defined open-cup flash-point. One believed to be a below flash-point result may well be one above the flash-point. This problem can be solved, however, if gas-phase fuel-concentration is monitored during the experiment. A micro-sampling technique is well established for species concentration measurement for stationary flames, but it may not be feasible for spreading flame, because it requires sampling time of at least several seconds.

What we propose here is a dual wavelength holographic interferometry (DWHI), an indirect technique whose response-time is less than a microsecond with spatial resolution less than 0.1 mm in identifying concentration difference (the corresponding spatial resolution for the micro-sampling is at best on the order of several millimeters). It also can be applied to three dimensional problems.

In this study we use a two dimensional model because our experimental condition approximates that state. The index of refraction, $n(x,y,\tau)$ can be written as:

$$[n - n_{\infty}] L = m\lambda. \quad (2)$$

Here $L (= L_1 + L_2)$ is tray width, and the rest of symbols are explained earlier. Using the Lorentz-Lorenz equation, Eq. (2) can be rewritten as:

$$(1/\rho) [(n^2 - 1) / (n^2 + 2)] = N/M. \quad (3)$$

Here N = molar refractivity, and M = molecular weight. Using the equation of state for an ideal gas and $n_{\infty} \approx 1$,

Flame spread experiments were conducted using a 4 cm wide tray filled with 1-propanol, the same apparatus used previously. A representative DW hologram is shown in Fig. 5, which is much more detailed and clearer than that for the single wavelength HI in Fig. 2. A few interesting aspects from this interferogram can be discussed.

(1) The interferogram in Fig. 5 shows an integrated temperature distribution along the laser beam. Previously, a high speed-video picture and IR photograph were taken for the flame spreading over the liquid [20,21]; they confirmed that the flame shape was approximately two dimensional (no significant difference along the beam) and liquid-surface temperature along the beam was also sustained nearly uniform (the largest temperature variation near the edge was

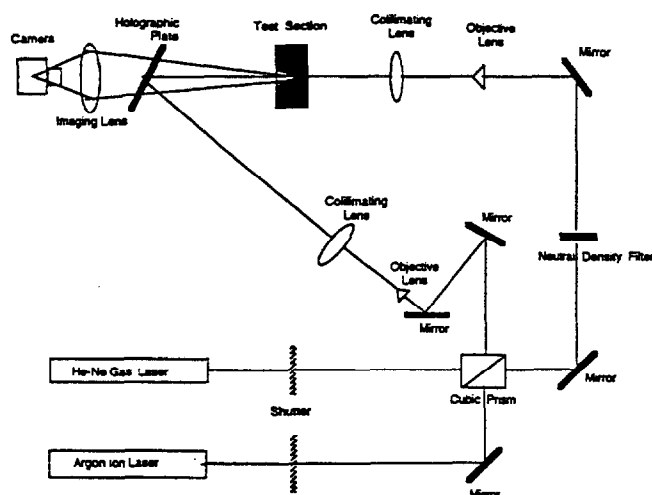


Figure 4 A schematic of DWHI.

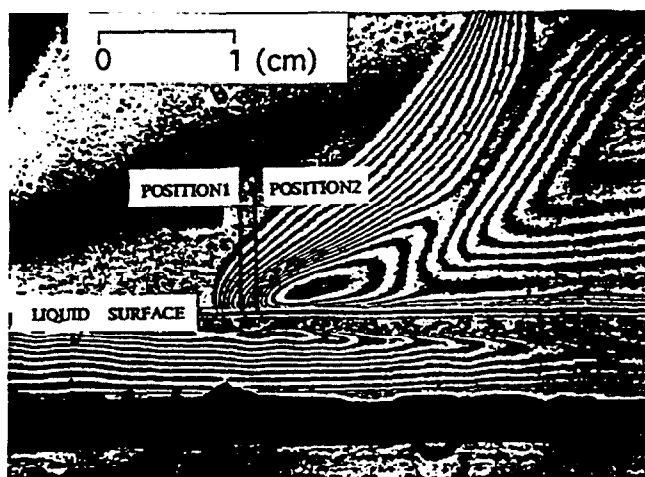


Figure 5 A DW interferogram taken for spreading flame over 1-propanol at initial liquid temperature, 21°C.

20% different from the center line value). Therefore, along the beam we expect approximately the same percentage variation in gas-phase temperature, which is not significant.

(2) There are two different fringe groups which are separated by a circular fringe zone. The one front of the circular shape is the main spreading flame, while the one behind the circular zone is part of a pulsating flame (precursor flame or finger flame [16]) which can be separated from our discussion here. The maximum temperature gradient location is located just in front of the circular fringe zone. The maximum temperature gradient is likely to occur on the fuel-lean side adjacent to the maximum flame-temperature location. Therefore, the flame-front location may be found somewhere between the maximum temperature-gradient location and the circular fringe zone. Formation of the circular fringe zone was also found in stationary pool fires [22,23], and so it is not unique to the spreading flame. It can be interpreted as a buoyancy-driven convection which is caused by a sudden expansion of the fuel vapor near a high temperature flame-zone.

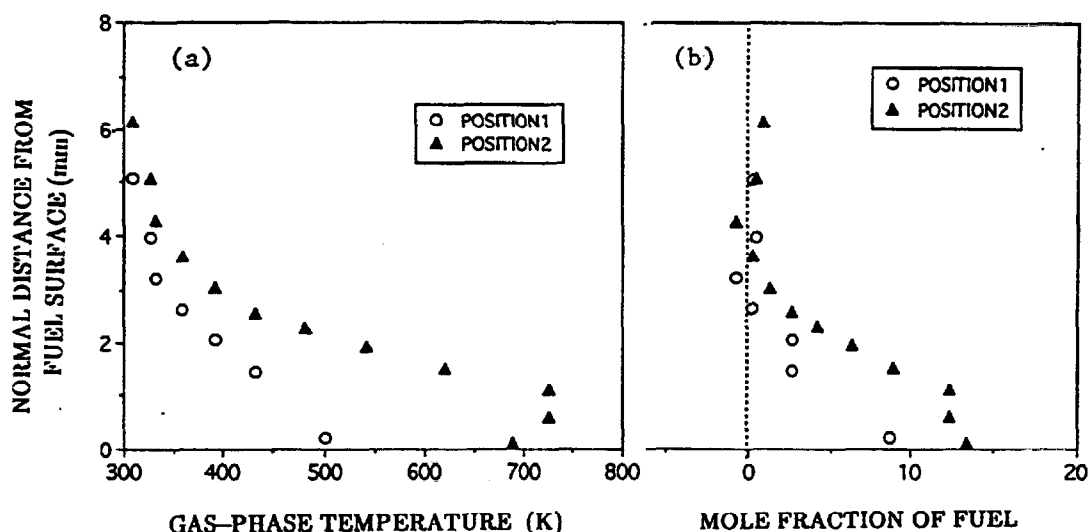


Figure 6 Vertical profiles of (a) gas-phase temperature and of (b) mole fraction of fuel, both constructed from the figure 5 HI at two different locations specified in the figure 5.

Figure 6 shows gas-phase temperatures and fuel-vapor concentrations, both measured at positions 1 and 2 as shown in Fig. 5, as a function of height from the fuel surface, y . The result in figure 6 is straightforward, since a narrow band-pass filter can eliminate fringes due to the change of fuel-vapor concentrations. The same procedure that was employed for the liquid temperature measurement was applied to obtain the result in Fig. 6. The result in Fig. 7 was obtained by assuming the gas-phase composition is only air and fuel vapor; however, this assumption may not be accurate because combustion by-products and fuel-pyrolysis products (generated in a high temperature region) can diffuse or convect

to the measurement location. Fortunately, because the measurement location is upstream from the flame front location and their temperatures are relatively low, the above assumption may not cause a substantial error. When the above assumption is not valid, a further complicated process is required to reduce the concentration data from DWHI, which is beyond the scope of this paper and will be discussed in Ref. [24].

CONCLUSIONS

(1) The HI technique was proven to be a very effective tool in nearly simultaneously obtaining a detailed and temporal temperature map over a region about the fuel-gas interface for studying both flame-spread and pool-fire phenomena.

(2) The single wavelength HI can accurately detect transient liquid-temperature profiles; while DWHI can detect transient profiles of both temperature and fuel concentrations in the gas phase. The thermocouple point-by-point temperature-measurement technique has limitations due to its spatial resolution; and species concentration measurement by micro-sampling has limitations due to both its spatial resolution and time response.

(3) Dual wave-length HI has proven to be a very useful technique for simultaneously measuring transient profiles of both temperature and fuel concentrations in the gas phase. When both combustion by-products and fuel-pyrolysis products affect the fuel concentrations, the accuracy of this technique for measuring the fuel concentrations decreases. Therefore, further work is needed to solve this problem.

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REFERENCES

- [1] A. Ito, D. Masuda and K. Saito, *Cumbustion and Flame*, 83: 375 (1991).
- [2] A. Ito, K. Saito and T. Inamura, *J. Heat Transfer*, 114: 944 (1992).
- [3] J.S. Newman, Laser Doppler Velocimeter Measurements of the Gas and Liquid Flow Fields Induced by Flame Propagation over a Liquid Fuel Surface, *MSE Thesis, Mech. and Aerospace Engineering Dept., Princeton*

- University, Princeton, NJ (1979).
- [4] A. Ito and T. Kashiwagi, *Combustion and Flame*, 71: 189 (1988).
 - [5] A. Ito and T. Kashiwagi, *Applied Optics*, 26: 954 (1988).
 - [6] T. Kashiwagi and T. Kashiwagi, *Nineteenth International Symposium on Combustion*, The Combustion Institute, p. 1511 (1984).
 - [7] D. Evans, G. Mulholland, D. Gross, H. Baum and K. Saito, Environmental Effects of Oil Spill Combustion, *Report NISTIR 88-3822*, National Institute of Standards and Technology, Gaithersburg, MD 20899, (1988).
 - [8] D. Evans, G. Mulholland, D. Gross, H. Baum and K. Saito, Burning, Smoke Production, and Smoke Dispersion from Oil Spill Combustion, *Report NISTIR 89-4091*, National Institute of Standards and Technology, Gaithersburg, MD 20899, (1989).
 - [9] T. Inamura, K. Saito and K.A. Tagavi, *Combustion Science and Technology*, 86: 105 (1992).
 - [10] W. Hauf and U. Grigull, *Advances in Heat Transfer*, Series 6, Academic Press, p. 268 (1970).
 - [11] C.G. Murphy and S.S. Alpert, *Journal of Physics*, 39: 834 (1974).
 - [12] A. Ito, S.K. Choudhury and T. Fukano, *Transaction of JSME*, Series B, 56: 194 (1990).
 - [13] A. Ito, K. Saito and C.J. Cremers, *Fire Safety Science - Proc. Fourth International Symposium*, The International Association for Fire Safety Sciences, pp. 455-456 (1994).
 - [14] T. Hirano, T. Suzuki, I. Mashiko and N. Tanabe, *Combustion Science and Technology*, 22: 83 (1980).
 - [15] K. Akita, *Fourteenth International Symposium on Combustion*, The Combustion Institute, p. 1075 (1972).
 - [16] H. Ross, *Progress in Energy and Combustion Science*, 20: 17 (1992).
 - [17] I. Glassman and F.L. Dryer, *Fire Safety Journal*, 3: 123 (1980).
 - [18] W.C. Gradiner, Jr., Y. Hidaka and T. Tanazawa, *Combustion and Flame*, 40: 213 (1981).
 - [19] T.L. Spatz and D. Poulikakos, *J. Heat Transfer*, 114: 998 (1992).
 - [20] F. Miller and H. Ross, Temperature Field During Flame Spread over Alcohol Pools: Measurements and Modeling, *Presented at the Eastern States Section, The Combustion Institute Meeting*, Florida, November (1994).
 - [21] A. Bouhafid, J.P. Vantelon, P. Joulain and A.C. Fernandez-Pello, *Twenty-second International Symposium on Combustion*, The Combustion Institute, pp. 1291-1298 (1988).
 - [22] S. Venkatesh, A. Ito and K. Saito, Why are Pool Fires Anchored?, submitted to *Combustion and Flame*, (1994).
 - [23] A. Narumi, G. Tashtoush, K. Saito and C.J. Cremers, Dual Wave-Length HI, to be published.